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# **A COMPARATIVE STUDY OF ACOUSTO- OPTIC TIME-INTEGRATING CORRELATORS FOR ADAPTIVE JAMMING CANCELLATION**

Rochester Institute of Technology

Guifang Li

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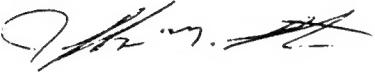
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## **1. INTRODUCTION**

Correlation is one of the most powerful tools at the disposal of a signal processing engineer. Mathematically speaking, correlation is nothing but the integral of the product of two functions, giving a measure of the similarity between them and hence it is in essence a process of comparison. In practice we are seldom interested in comparing two pure mathematical functions as such. But when these functions represent real time electrical signals commonly encountered in communications, image processing and pattern recognition, noise estimation and processing etc. the comparison of them assumes enormous significance. Any system or mechanism which is capable of performing this type of comparison can be described as a Correlator. Though this operation can be realized through different basic techniques our interest is focused on the optical correlation especially Time Integrating Acousto-Optic Correlation.

Optical techniques for correlation are considered attractive because of the relative compactness and simplicity of processing systems which can provide instantaneous correlation information of wide bandwidth(GHz) signals. Another advantage of optical correlators, compared with their digital counterparts is that a high resolution Fourier transform operation on an optical image may be rapidly executed, typically in nanoseconds, by simply transmitting the input image through a single lens. However, the overall speed of an optical correlator is still limited by the input and output electronics like spatial light modulators, the camera or detector arrays used for the

imaging of the optically computed correlation function. etc. Acousto-optic correlators are particularly useful at microwave frequencies commonly encountered in radar applications. Over the years many techniques have been proposed for the realization of optical correlation using acousto-optic devices. These devices naturally lend themselves to correlation because of the natural ability of optics to achieve multiplication through interference, coupled with the simultaneous achievement of many different time delays in an acoustic device.

Configurations of acousto-optic correlators fall into two broad categories. The first type, spatial integrating correlators perform correlation by integrating light diffracted by all parts of  $t^1 \cdot t^2$  signals which are simultaneously present in the acoustic device. These types of correlators have a large range window, but the time bandwidth product is limited by device parameters. Depending upon the technique used for providing the necessary reference signal they can be again classified as either fixed reference or traveling acoustic wave reference spatial correlators. The second type, time integrating correlators, uses a photodetector array to perform an integration in time for each point within a cell. This provides a limited range window but a considerably large time bandwidth product. Depending upon the configuration these correlators can be in-line or Mach-Zehnder interferometric. These different configurations will be dealt with in detail in the following chapters. The basic design of a particular signal correlator involves the selection of a particular configuration which achieves optimum utilization of the limited acousto-optic device parameters for the given application.

In this report we are describing the setting up of a time integrating correlator using the Mach-Zehnder interferometric configuration, and are investigating the effects of different frequency vibrations applied to one of the acoustic cells.

## 2. FUNDAMENTALS AND THEORETICAL ANALYSIS

### 2.1 BASIC CONCEPT OF CORRELATOR

Let us consider the correlation of two analog signals  $S_1(t)$  and  $S_2(t)$  as shown in the following figure.

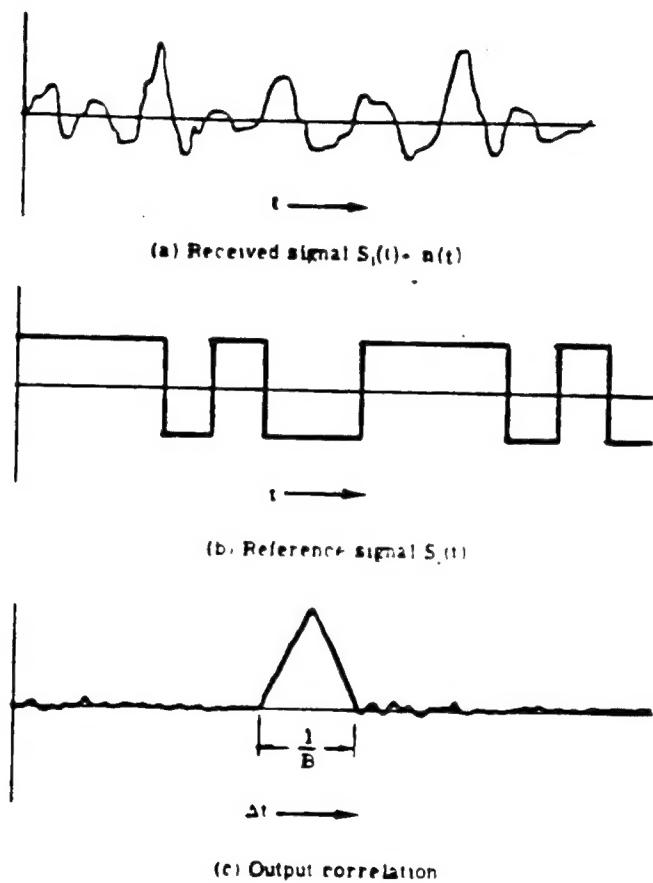


Figure 1. Correlation of a Noisy Signal With a Reference Signal.

Let the signal  $S_1(t)$  represent the received signal in a communication or radar system. Generally this signal will have a useful information signal  $s(t)$  contaminated by a noise signal  $n(t)$  which is to be removed. The signal  $S_2(t)$  is a reference signal, normally the

complex conjugate of the information signal  $S(t)$ . The correlation of these two signals is given by the integral equation,

$$R(\tau) = \int [S_1(t) + n(t)]S_2(t + \tau) dt$$

The basic features of this correlation function can be described as follows. The width of the correlation peak in time is given by

$$\text{Correlation function width} = \Delta t = 1/B$$

The signal to noise ratio of the correlation peak with respect to the input signal is given by

$$SNR = B \cdot T \cdot SNR_1.$$

Where  $B$  is the bandwidth of the signals correlated,  $\tau$  the time delay introduced,  $T$  is the time duration of the signals correlated, and  $SNR_1$  is the signal to noise ratio of the received signal.

These two parameters indicate the reason for performing correlation and its significance in signal processing. First the correlation enables the achievement of a very narrow output pulse, even when the original signal is very long in time. Second, an increase in signal to noise ratio, called the correlation gain or processing gain, is achieved over the original received signal. These two properties enable a radar or communication system to transmit long pulses, and achieve the same sensitivity in time as a single short transmitted pulse, with an increase in signal to noise ratio compared to it. For radar systems, this means that peak power limitations on the transmitter are

reduced, providing for larger range and lower power transmitters. For communication systems, the correlation gain enables achievement of lower transmitter power levels.

In configuring a correlator, these two parameters are of primary importance. Two other characteristics must also be considered however. In most cases, only a certain time error is allowed between the received and reference signals, if a correlation peak is to be obtained. This allowable error in time is called the 'range window.' A second parameter of importance is the time window of the correlator, or total length in time of the correlated signal. This parameter is of great significance in Doppler sensitive systems.

## 2.2 CONFIGURATIONS OF AO CORRELATORS

The basic parameters of a correlator; like bandwidth, time bandwidth product, range window, and time window are in general determined by the limited band width and time bandwidth product of the particular acousto-optic device(s). The effects of these parameters on the performance of the correlator system characteristics are different, however, for different system configurations. Configurations of acousto-optic correlators fall into two broad categories. The first type, spatial integrating correlators which perform correlation by integrating light diffracted by all parts of the signals which are simultaneously present in the acoustic device. These type of correlators have a large range window, but the time bandwidth product is limited by device parameters. The second type, time integrating correlators use a photodetector array to perform an

integration in time for each point within a cell. This provides a limited range window but a considerably large time bandwidth product. The basic design of a particular signal correlator involves the selection of a particular configuration which achieves optimum utilization of the limited acousto-optic device parameters for the given application.

### 2.2.1 SPACE INTEGRATING CORRELATORS.

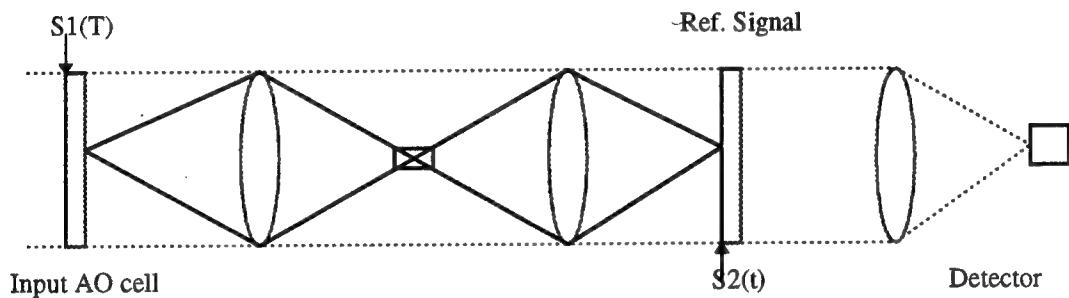


Figure 2. Space Integrating Acousto-optic Correlator Lay-out.

In this configuration of acousto-optic correlators, the received signal to be correlated is fed into the acoustic optic device, producing a spatial display of a given time window of the received signal. This spatial display is multiplied by the reference signal, existing either as a fixed mask or as another acoustic wave in another acousto-optic cell. The integration of the output is performed by an imaging lens that collects the light in the aperture and brings it to a single point in the back focal plane, with respect to the spatial coordinate over the aperture and hence the name space integrating correlator. A theoretical analysis of such an acousto-optic correlator is given below. The schematic diagram of a simple space integrating correlator is given in figure 2.

$S_1(t)$  the signal to be correlated is fed into the acoustic cell, producing a traveling acoustic wave within the material. This results in a phase modulation of the incident illumination with a transmitted amplitude distribution

$$a(t) = a_0 \exp[i(\omega t + \alpha S_1(x + vt))]$$

This phase modulation is read out as an amplitude variation by using Schlieren readout. That is assuming small phase modulation

$$a(t) \approx a_0 e^{i\omega t} [1 + i\alpha S_1(x + vt)]$$

Now the optical Fourier transform of this amplitude distribution gives

$$F[a(t)]_T = a_0 e^{i\omega t} \{\delta(0) + i\alpha F[S(x + vt)]\}$$

where  $F[\cdot]$  is a finite Fourier transform taken over the time window  $T$  of the acoustic cell, and  $\delta(0)$  is the zero order light. By blocking this zero order light in the transform, an image amplitude results which is given by

$$i(x) = i a_0 e^{i\omega t} \alpha S_1(x + vt).$$

If we consider the fixed reference correlator, the reference signal exists as a spatial mask whose transmittance is given by

$$t(x) = 1 + S_2(x).$$

This reference is placed in the image plane of the acoustic device, resulting in the transmitted amplitude

$$i_1(x) = [1 + S_2(x)] i a_0 e^{i\omega t} \alpha S_1(x + vt).$$

A lens is placed behind the image plane to collect all the zero order transmitted light onto a detector. This results in an integrated amplitude given by the zero order term in the light Fourier transform as

$$F[i_1(x)]_{\omega=0} = ia_0 e^{i\omega t} \alpha \left[ \int_0^{vt} S_1(x+vt) dx + \int_0^{vt} S_2(x) S_1(x+vt) dx \right].$$

The first integral term is zero because  $S_1(t)$  has no bias level thus a square law detector placed at the zero order position provides the output current

$$i(t) = a_0^2 \alpha^2 \left| \int_0^{vt} S_2(x) S_1(x+vt) dx \right|^2$$

which is the square of the required correlation function. In the above analysis  $a_0$  is the incident amplitude,  $\omega$  is the light frequency,  $\alpha$  is a constant, and  $v$  is the acoustic velocity.

The characteristics of a space integrating correlator using a fixed reference mask are described below. In such a system the maximum signal bandwidth and time window are determined by those of the acoustic cell, assuming the photodetector used for the imaging is having a large enough bandwidth. Hence the time bandwidth product is that of the acoustic cell. The most desirable feature of this system is that the range window is unlimited, since the signal eventually flows through the cell producing a correlation output no matter what its time uncertainty may be. The correlation of a given signal with many reference signals can be realized very easily by this configuration, by using different reference masks placed side by side in the reference plane. By using cylindrical optics which image each strip reference mask onto its own detector in the horizontal direction, each detector output corresponds to a particular correlation function. This multiplexing capability can be very useful when a variety of different signals are required to be correlated in a particular application.

In the second type of space integrating acousto-optic correlator the fixed mask is replaced with another acoustic cell. If a time reversed replica of the appropriate reference signal is fed into the device, the two signals will slide by each other, providing a correlation signal at the output detector. The advantage of using such a technique compared to the fixed mask method is that any signal of interest can be correlated without the need for the fabrication of a photographic reference mask. A second advantage is that the correlation function actually appears as an envelope modulation of a carrier produced by the Doppler shift between the two signals. This enables the heterodyne detection of the output to provide the correlation function. As in the case of the fixed reference correlator the bandwidth and the time window are limited by the acoustic cell parameters. The main difference between these spatial correlators lies in the necessity that both the reference signal and the input signal be in the cells simultaneously , for the later configuration. If the signals are of infinite length in time this condition is automatically met. But for more realistic short signals, however, a loss in output will occur as the time difference between the signals increases, since only partial correlation will occur. In the limiting case of very short pulses a timing difference greater than the acoustic cell time window will completely prevent correlation.

## 2.2.2 TIME INTEGRATING ACOUSTO-OPTIC CORRELATOR.

One of the main drawbacks of the space integrating acousto-optic correlators is the limitation in time bandwidth product. Integration in time rather than in space can be used to realize extremely large time-bandwidth products. Time integrating techniques have been generalized for one and two dimensional signal processing. What make the time integrating architecture preferable are the attractive device technology and the flexibility of the time integrating algorithms. An important consequence of the time integrating techniques is the ability to operate on signals with very large time bandwidth products without having to store the entire time history as a spatial record. Acousto-optic devices and charge coupled image sensors are particularly well suited for time integrating correlator implementation. Time integrating optical correlators were first demonstrated using translating optical masks and scanning detector systems. Acousto-optic implementations of one dimensional time integrating correlation and spectral analysis have first been introduced by Montgomery, Sprague and Koliopoulos.

Depending upon the system configuration time integrating acousto-optic correlators can be of two types, In-line and Interferometric. In the in-line architecture the signal to be correlated is directly intensity modulated onto the laser diode and the reference signal is provided as the acoustic signal in an acousto-optic cell. In the interferometric configuration both the input signal and the reference signal exist as acoustic waves in two acousto-optic cells interposed in the two branches of a Mach-Zehnder interferometer. In all approaches to time integrating correlation the goal is to achieve a

term in the detected light intensity that is proportional to the product of the input signals. Acousto-optic devices modulate optical phase and hence are basically non-linear modulators of electric field amplitude or intensity. However, linear electric field modulation is approximated at low diffraction efficiency. In the interferometric schemes, it is assumed that acousto-optic modulation of the electric field is linearly proportional to the drive voltage, and that the imaging optics pass only the first diffraction order. This condition is approximated at low diffraction efficacy.

#### 2.2.2.1 IN-LINE TIME INTEGRATING CORRELATOR.

The implementation described uses an internally modulated laser diode source as shown in the following figure.

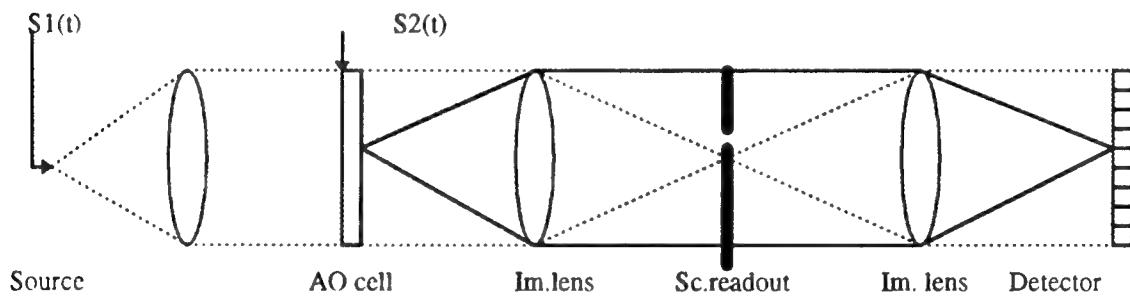


Figure 3 . In-line Time Integrating Acousto-optic Correlator Lay-out.

A reference oscillator signal is added to the acousto-optic deflector input with a frequency that is offset from the signal modulation; in addition the illumination source must be modulated on a carrier with equal frequency offset. The laser diode is temporally modulated by the signal  $S_1(t)$ , to produce an output intensity  $I_1(t)$ , which illuminates an acoustic delay line modulator. A second signal,  $S_2(t)$ , introduced into the acoustic cell which spatially modulates the source intensity by an amount

denoted by  $I_2(t - x/v)$ , where  $x$  is the spatial dimension of the acoustic cell window and  $v$  is the acoustic velocity. The acoustic signal is schlieren imaged onto a linear photodiode array, the intensity distribution in the image plane is given by the product  $I_1(t)I_2(t - x/v)$ . The charge integration directly proportional to exposure, is performed by detectors at discrete positions resulting in a spatial sampling of the correlation function. The resultant voltage at the  $i^{\text{th}}$  detector element is given by

$$R_{12}(\tau_i) = \int_0^T I_1(t) I_2(t - x_i/v) dt$$

where  $\tau_i = x_i/v$  and  $T$  is the integration time of the detector, set by the timing of the charge transfer readout register. This is the required correlation, where  $I_1$  and  $I_2$  are directly related to the input signals.

The image intensity distribution,  $I$  is given by the product of the source modulation,  $I_1$  and acousto-optic modulation denoted by  $I_2 = |E_2|^2$  where  $E_2$  is the complex electric field intensity.

$$I(t, x) = I_1(t) I_2(t - x/v)$$

For double sideband modulation

$$I_1(t) = A_1 [1 + \sqrt{2} m_1 S_1(t) \cos(2\pi f_0 t)]$$

$$E_2(t) = \sqrt{A_2} [1 + \sqrt{2} m_2 S_2(t) e^{i2\pi f_0 t}] e^{i2\pi f_c t}$$

$$I_2(t) = |E_2(t)|^2 = A_2 [1 + 2m_2^2 S_2^2(t) + 2\sqrt{2}m_2 S_2(t) \cos(2\pi f_0 t)]$$

where  $f_0$  is the frequency difference between the reference oscillator at  $f_c$  and the double sideband suppressed carrier modulation at  $f_c + f_0$ . The +1 diffraction order is passed by the imaging optics.  $A_1$  and  $A_2$  correspond to light intensity and diffraction efficiency respectively;  $m_1$  and  $m_2$  are constants that determine the modulation depth. It is assumed that signals  $S_1$  and  $S_2$  are bandlimited to a bandwidth of  $B$ , and have unit average power.

For  $f_0 > 3B$  several cross terms effectively integrate to zero and the output becomes,

$$R(\tau) \equiv A_1 A_2 \left[ T + 2m_2^2 \int S_2^2(t-\tau) dt + 2m_1 m_2 \cos(2\pi f_0 \tau) \int S_1(t) S_2(t-\tau) dt \right].$$

The first two terms of the above equation are bias and the last term is the required correlation on a spatial carrier  $f_0$ . The bias terms can be eliminated through filtering.

The ratio of signal to bias for maximum correlation is given by

$$\beta = \frac{2 m_1 m_2}{1 + 2 m_2^2}.$$

#### 2.2.2.2. TWO-PATH TIME INTEGRATING CORRELATOR.

In this correlator configuration both the signal to be correlated and the reference signal are applied to two separate acousto-optic cells interposed in the two branches of a Mach-Zehnder interferometer. The interference of the output beams of the two acousto-optic cells will contain the required correlation information as shown in the following theoretical analysis.

Analysis of an Acousto-Optic correlator using the Mach-Zhender configuration is given below. The two AO cells are provided with different acoustic frequencies,  $\omega_{A1}$  and  $\omega_{A2}$ , as against the present system in which the AO cells are driven with the same acoustic frequency. Let  $S_1(t)$  and  $S_2(t)$  be the signals to be correlated.

The intensity of the output beam (+1 order diffraction) of the two AO cells are

$$U_1 = S_1(t - \tau) \exp[j\omega_{A1}(t - \tau)]$$

$$U_2 = S_2(t + \tau) \exp[j\omega_{A2}(t + \tau)].$$

After the two beams are combined together to form interference fringes, the intensity is given by

$$U = |U_1 + U_2|^2 = |S_1(t - \tau)|^2 + |S_2(t + \tau)|^2 + 2 \operatorname{Re}\{S_1(t - \tau)S_2^*(t + \tau) \exp[j\omega_{A1}(t - \tau)] \exp[-j\omega_{A2}(t + \tau)]\}$$

After the CCD array is exposed for a time 'T' (the integration time), the above equation becomes

$$U' = \int_0^T |S_1(t - \tau)|^2 dt + \int_0^T |S_2(t + \tau)|^2 dt \\ \cos(\omega_{A1} + \omega_{A2})\tau \int_0^T S_1(t - \tau)S_2^*(t + \tau) \cos(\omega_{A1} - \omega_{A2})t dt \quad (1)$$

When the period of the temporal carrier is much greater than the integration time equation (1) changes to

$$U' = \int_0^T [|S_1(t - \tau)|^2 + |S_2(t + \tau)|^2] dt + \cos[(\omega_{A1} + \omega_{A2})\tau] \times \\ \cos(\Delta\omega_A t) \times R(\tau) \quad (2)$$

Where  $\Delta\omega = \omega_{A1} - \omega_{A2}$  and  $R(\tau) = \int_0^T S_1(t-\tau)S_2^*(t+\tau)dt$  is the correlation

function. If we assume  $\Delta\omega = \omega_{A1} - \omega_{A2} = 0$  in equation (2),

$$U' = \int_0^T [ |S_1(t-\tau)|^2 + |S_2(t+\tau)|^2 ] dt + \cos(2\omega_A\tau) \times R(\tau) \quad (3)$$

The above equation describes the present system and clearly shows that the correlation function is modulated only on the spatial carrier. The first term in the equation represents the power of the signals. The contribution due to the two terms in the detected signal are of the same order and hence to get a good signal to noise ratio the first term should be filtered out. In the implementation of this system the removal of the bias (due to the power term in equation 3) becomes a difficult problem (especially for random noise signals), since electronic filtering cannot be used owing to the absence of any temporal carriers.

But from equation (2) it is clear that the correlation function is modulated both spatially and temporally. The spatial carrier frequency is the sum of the two acoustic frequencies and the temporal carrier frequency is the difference between them. This temporal modulation provides us with a powerful means by which the signal to noise ratio can be improved and the two biasing terms (the first two terms in equation 1) corresponding to the power of the signals  $S_1$  and  $S_2$  can be removed. Due to the presence of the temporal carrier the bias can be electronically filtered out. This can be done by using a lock-in amplifier locked onto the temporal carrier frequency  $\Delta\omega$ ,

which suppresses the low frequency power components and eliminates noise components of all other frequencies.

If we assume the integration time ' $T$ ' to be one tenth of the temporal carrier period ' $T_A$ ', for a difference of '1000Hz' in the acoustic frequencies we have to use a CCD array of integration time of the order of 0.1ms.

The additional components needed for the implementation of the modified correlator are

- 1) Lock-in Amplifier
- 2) AO cells and drivers with two precisely controlled close frequencies
- 3) CCD array camera which can operate with integration times of the order of 0.1 ms.

The present system uses the vertical interference fringes formed by the superimposition of the images of the two AO cell windows. The continuous correlation function is spatially sampled by the vertical fringes so that the sampling condition is met. This is not the only spatial sampling involved. The correlation function sampled by the interference pattern is again spatially sampled by the CCD array due to the presence of discrete pixels. The effect of these two samplings is shown below.

As is clear from the figure given below there is a fair probability of the fringes being focused onto the space between the pixels resulting in the loss of information. In order to meet the sampling condition and make sure at least one fringe is properly focused

onto a single pixel we must focus 3-4 fringes onto a single pixel. If a CCD array of 1024 pixels is used, this demands above 3000 fringes focused onto the CCD window. Moreover the fringes should be exactly vertical in order to keep an integer number of fringes into a single pixel. All these conditions requires tedious and meticulous adjustments of the interferometer especially the beam combiner, which makes the system more vibration sensitive.

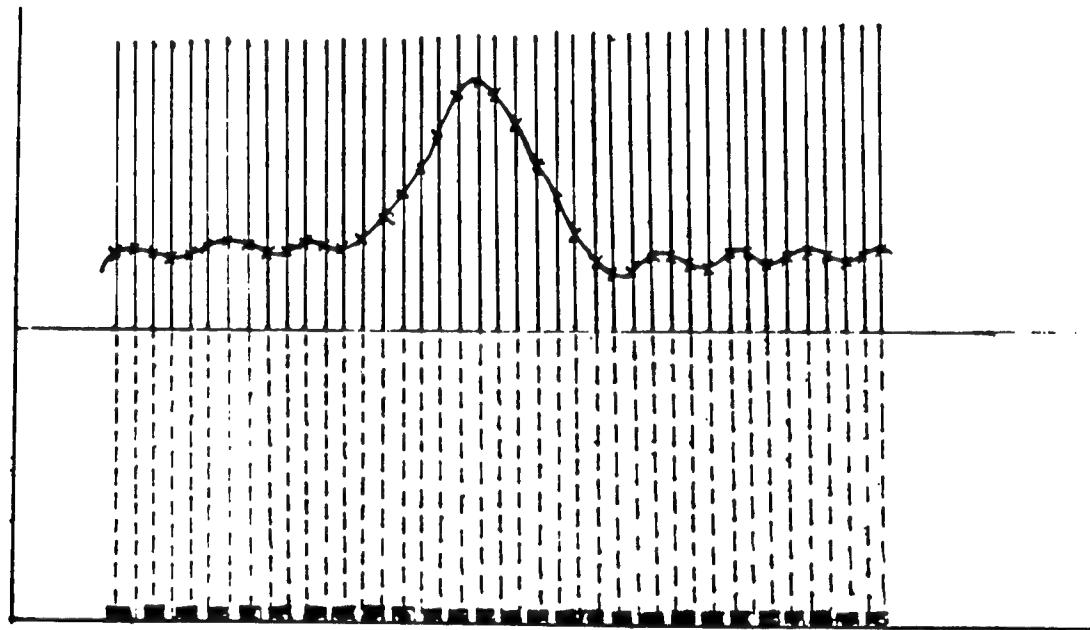


Figure 4. Spatial Sampling due to Imaging of the Fringes by Individual CCD Pixels

On the other hand if we use the horizontal fringes the first type of spatial sampling, i.e. by the vertical fringes, is avoided. Now the intensity of the single horizontal fringe would vary continuously in accordance with the correlation function and will be sampled by the pixels of the CCD array producing a more faithful representation of the correlation function.

### 3. EXPERIMENTAL SETUP AND RESULTS.

#### 3.1 SETUP

The experiment described below was conducted to investigate the effect of vibration applied to the acoustic cell in the correlation function of a Mach-Zehnder interferometric time integrating correlator. The optical component layout is given in the following figure.

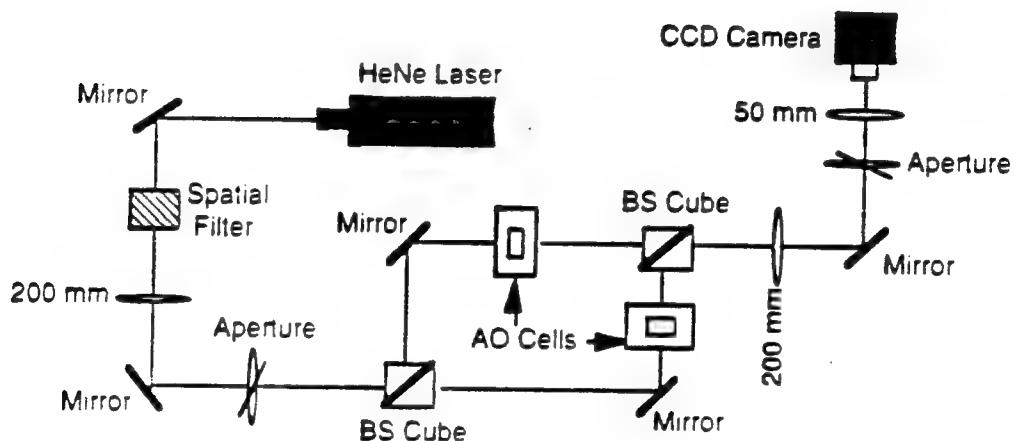


Figure 5. Optical Lay-out of the Experimental Set-up.

The light from a laser source is split into two paths by a beam splitter to form the two branches of the Mach-Zehnder interferometer. The laser source used is a 14 mW continuous wave at 632.8 nm. This beam is then spatially filtered and suitably collimated. The collimated light is split to form the two branches of a Mach-Zehnder interferometer. Each of these paths contains an acousto-optic cell. One of these is fed with the signal to be correlated and the other with the reference signal. The acoustic cells used are single channel,  $TiO_2$  longitudinal mode deflectors manufactured by Brimrose Corporation. The deflectors have a 5 microsecond time aperture and a 30

MHz bandwidth centered around 80 MHz. One of the AO cells is mounted on a Physik piezoelectric stand which can provide the desired vibrations.

In the present setup we used the same pulse trains in both cells so that the system output is the autocorrelation. The low frequency (1-5 MHz) pulses are modulated onto a sinusoidal carrier at 70 MHz using the acoustic cell driver oscillator/amplifier which provides a balanced modulated output at 2 to 4 Watts of power according to the acoustic cell specifications. The counter-propagating +1 diffracted orders and the undiffracted light from the two acoustic cells are then recombined by a beam combiner, whereby the outputs of the acoustic cells interfere with each other to form fringes. The undiffracted beam is blocked at the focal plane of an imaging lens, using an appropriate stop. The resulting fringe pattern is imaged onto the aperture of a linear CCD array using a cylindrical lens to obtain a uniform distribution across the array. The CCD used is a 1x 512 pixel EG&G LC 1901 FKN-011. The CCD camera is interfaced to a personal computer through a Girard 3197 8-bit A/D converter interface board.

### 3.2 RESULTS

#### 3.3 3.2.1 The Effects of Vertical Vibrations

The vertical vibration is simulated by placing the AO cell on the piezoelectric transducer which is in a vertical position. The vibration in the vertical direction is found to be harmless if the vibration magnitude is small enough so that the laser beam always fills the AO cell window. In other words, in designing the correlator

architecture, the vertical dimension of the laser beam should be larger than the size of the AO cell window by at least the excursion of vibrations expected.

### 3.2.2 The Effects of Horizontal Vibrations

The horizontal vibration is simulated by placing the AO cell on a leveled platform with ball bearings between them, and the piezoelectric transducer is attached to the AO cell horizontally. The frequency of vibrations can be controlled by an externally applied sinusoidal signal. The correlation pattern for different frequencies are observed with and without the vibrations applied. The results are shown in figures x-y for signal frequencies of 1 MHz, 2 MHz, 3 MHz, 4 MHz, and 5 MHz respectively, in which the correlation function is given by the gray scale intensity plotted against the pixel location. For each signal frequency, the autocorrelation function is plotted at vibration frequencies of 20 Hz, 200 Hz, 1 kHz, and 2 kHz along with the autocorrelation function with no vibrations applied. The maximum displacement for each frequency is fixed at 80 micron. The functional form of the autocorrelation remains unchanged with vibration. However, the strength of the autocorrelation depends on the vibration. At low signal frequencies, such as at 1 MHz, the autocorrelation function with vibration fluctuates in an unpredictable manner. For high-frequency signals (2-5 MHz), the strength of autocorrelation with vibration is the same under different vibration frequencies but is different from that with no vibration. The difference in the strength of autocorrelation, with and without vibration, decreases as the signal frequency is increased.

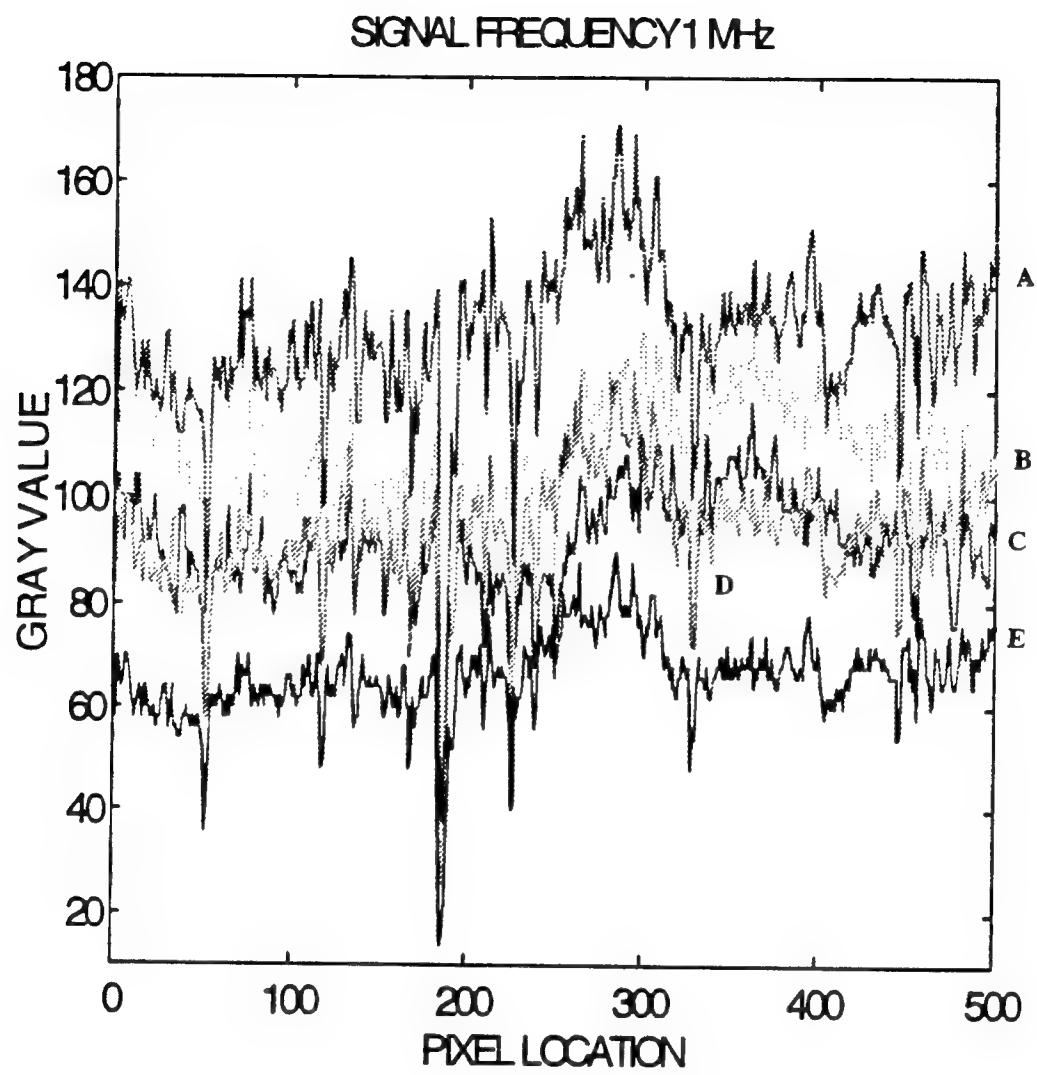


Figure 6. Auto-Correlation of a 1MHz Pulse Train, Subjected to Different Vibration Frequencies. A - 2KHz , B - No Vibration, C - 200 Hz, D - 20 Hz, E - 1KHz .

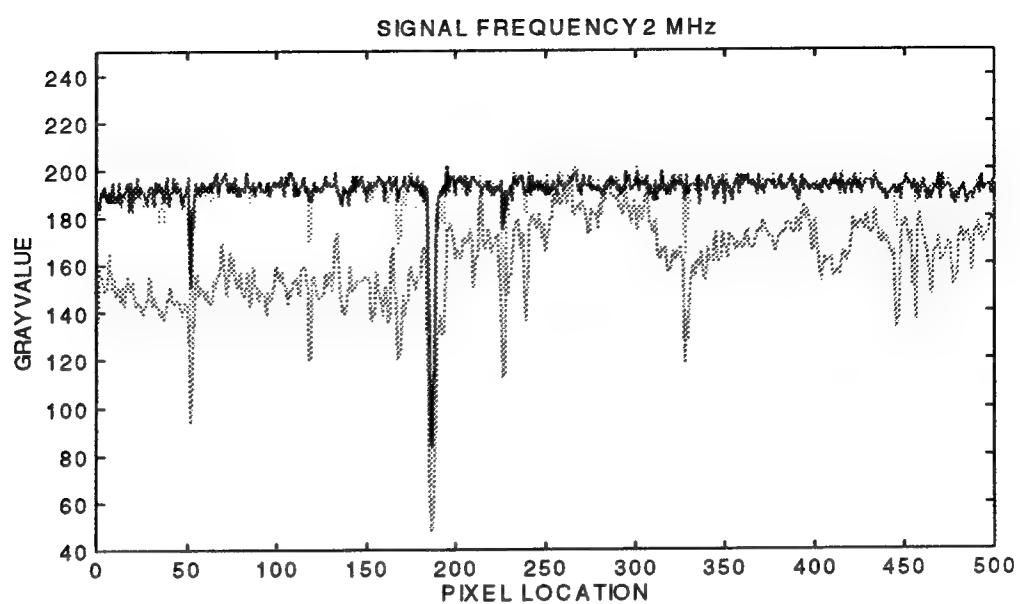


Figure 7. Auto-Correlation of a 2MHz Pulse Train With Different Vibration Frequencies.  
A-Vibrations of 20Hz, 200Hz, 1KHz and 2KHz Super imposed

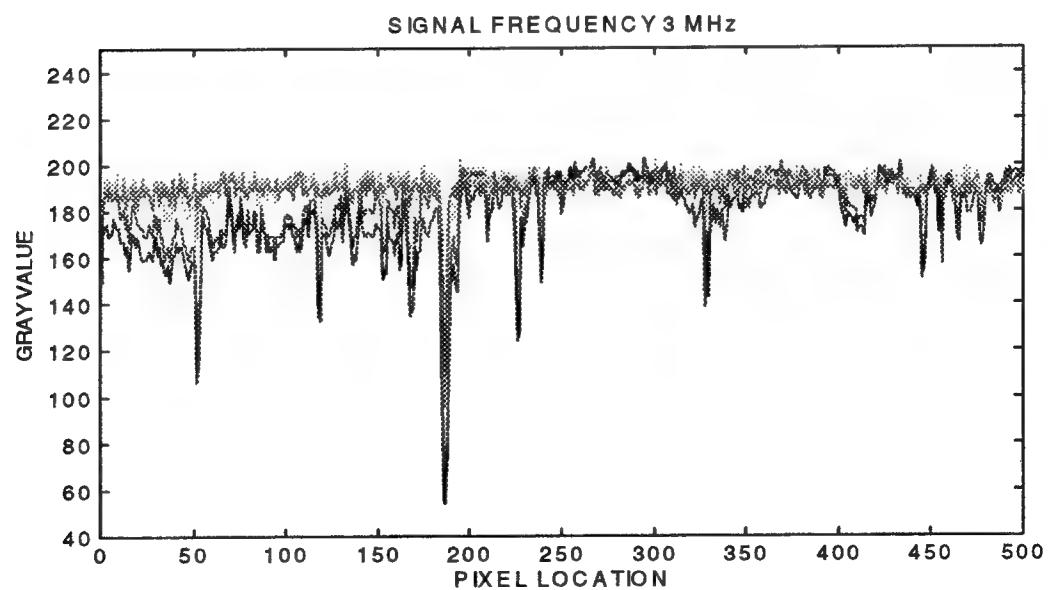


Figure 8. Auto-Correlation of a 3MHz Pulse Train With Different Vibration Frequencies.

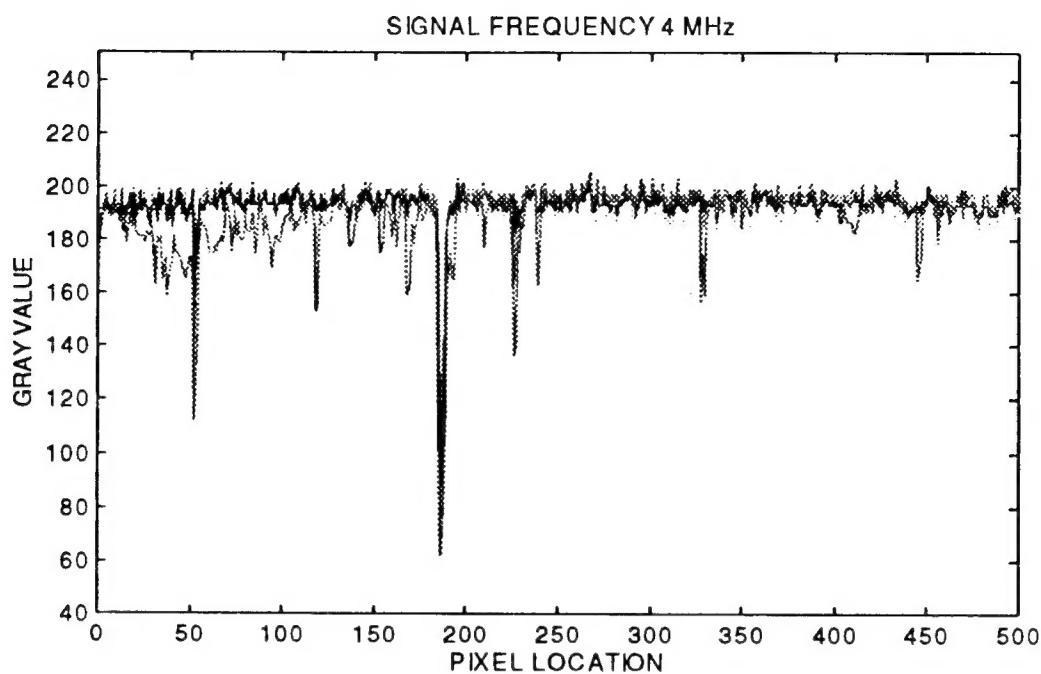


Figure 9. Auto-Correlation of a 4MHz Pulse Train With Different Vibration Frequencies.

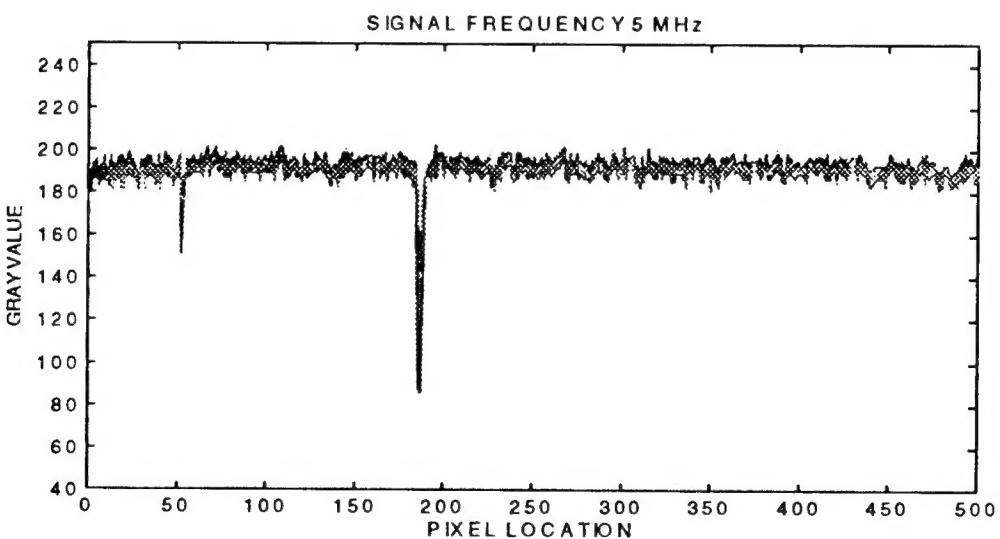


Figure 10. Auto-Correlation of a 5 MHz Pulse Train With Different Vibration Frequencies.

### 3.3 CONCLUSION

The vibration frequencies (20 Hz-2 kHz) simulated in this work is representative of vibrations likely encountered in a battlefield environment. The signal frequencies chosen are also the typical baseband information frequencies of radar's. From figure 3.1 it is evident that the vibration applied to one of the acoustic cells is having a significant influence in the intensity of the resulting correlation function. Though the intensity is affected, the general shape of the correlation function is accurately preserved. But as the signal frequency is further increased the effect of external vibration reduces considerably and at high signal frequencies, say for example at 5 MHz (figure 3.5) the effect of vibration is negligible.

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